IMPROVING ENERGY EFFICIENCY VIA OPTIMIZED CHARGE MOTION AND SLURRY FLOW IN PLANT SCALE SAG MILLS

ANNUAL REPORT

Reporting Period Start Date: 22 July 2004
Reporting Period End Date: 21 July 2005

Raj K Rajamani, Project Manager
Sanjeeva Latchireddi, Project Leader
Sravan K Prathy, Graduate Student
Trilokyanath Patra, Graduate Student

December 2005

DE-FC26-03NT41786

University of Utah
135 S 1460 E Room 412, Salt Lake City 84112

DISCLAIMER

ABSTRACT

The U.S. mining industry operates approximately 80 semi-autogenesis grinding mills (SAG) throughout the United States. Depending on the mill size the SAG mills draws between 2 MW and 17 MW. The product from the SAG mill is further reduced in size using pebble crushers and ball mills. Hence, typical gold or copper ore requires between 2.0 and 7.5 kWh per ton of energy to reduce the particle size. Considering a typical mining operation processes 10,000 to 100,000 tons per day the energy expenditure in grinding is 50 percent of the cost of production of the metal.

A research team from the University of Utah is working to make inroads into saving energy in these SAG mills. In 2003, Industries of the Future Program of the Department of Energy tasked the University of Utah team to build a partnership between the University and the mining industry for the specific purpose of reducing energy consumption in SAG mills. A partnership was formed with Cortez Gold Mines, Kennecott Utah Copper Corporation, Process Engineering Resources Inc. and others.

In the current project, Cortez Gold Mines played a key role in facilitating the 26-ft SAG mill at Cortez as a test mill for this study. According to plant personnel, there were a number of unscheduled shut downs to repair broken liners and the mill throughput fluctuated depending on ore type. The University team had two softwares, Millsoft and FlowMod to tackle the problem. Millsoft is capable of simulating the motion of charge in the mill. FlowMod calculates the slurry flow through the grate and pulp lifters. Based on this data the two models were fine-tuned to fit the Cortez SAG will.

In the summer of 2004 a new design of shell lifters were presented to Cortez and in September 2004 these lifters were installed in the SAG mill. By December 2004 Cortez Mines realized that the SAG mill is drawing approximately 236-kW less power than before while maintaining the same level of production.

In the first month there was extreme cycling and operators had to learn more. Now the power consumption is 0.3-1.3 kWh / ton lower than before. The actual SAG mill power draw is 230-370 kW lower. Mill runs 1 rpm lesser in speed on the average. The re-circulation to the cone crusher is reduced by 1-10%, which means more efficient grinding of critical size material is taking place in the mill. All of the savings have resulted in reduction of operating cost be about \$0.023-\$0.048/ ton.

TABLE OF CONTENTS

1. INTRODUCTION

There are a number of SAG mills in operation around the world whose diameter reaches up to 40 ft. These operations continually invest in new technologies to improve their energy efficiency and capacity in their SAG circuit. Commercial SAG mill performance is determined by a large number of variables, both mine site variables and mill variables. In many cases these variables dictate production capacity seemingly randomly. Therefore a number of operating philosophies, each specific to a plant, have arisen. In almost all concentrators the SAG operation is a continually evolving operation. Every year, ways and means are sought to increase capacity, decrease energy consumption and prolong lifter and liner life. Ore blending, newer designs of lifters, recycle crushing and redesign of grates and trommel screens are a few routes taken at considerable expense.

1.1 Operation of SAG Mills

The processing capability of a semi-autogenous (SAG) mill is greatly affected by ore geology and operating variables within the mill. The key issues can be broadly classified in to two categories: field of breakage/ charge motion and flow through the grate and pulp lifters. The field of breakage and charge motion is primarily affected by the design of shell lifters and mill speed. Once the ore is ground to a size that can pass through the grate holes, the slurry flows into the pulp lifter chamber that transports into the discharge trunnion. These components of the SAG mill are schematically shown in Figure 1.1 for easier understanding.

Once the slurry has made its way via the grinding media charge, its first stage of discharge is via the grates. Hence in the absence of any subsequent restriction the maximum flow capacity that can be obtained for a given mill is determined by the grate design. Here the design variables are open area and radial distribution of slots. The driving force for slurry transport from the mill shell through the grate holes is the difference in pressure head across the grate.

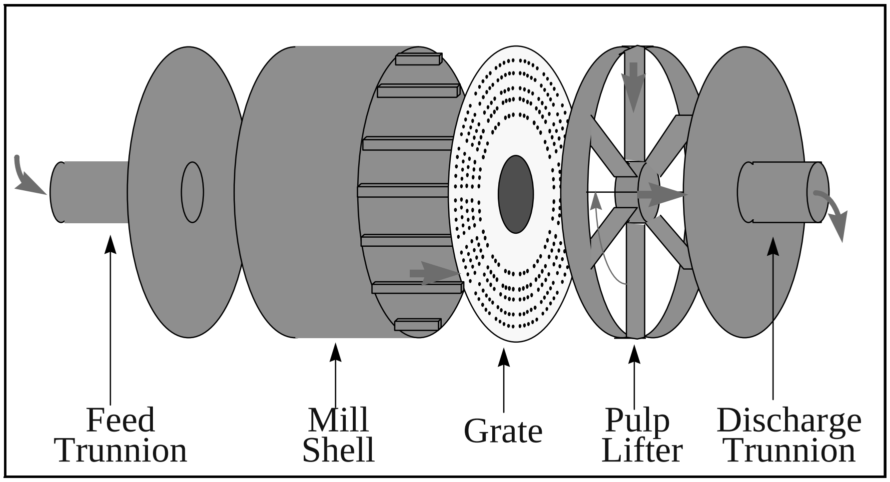

Figure 1.1: Schematic of a typical SAG mill.

1.1.1 **Field of breakage**: The motion of charge or rocks and balls in SAG mils can be viewed as a field of breakage generated as a result of the internal profile of the lifters and the rotational speed of the mill shell. The ore entering through the feed port is ground by this field and, after being sufficiently ground to the grate slot size, the slurry leaves through the slots in the grate. The field of breakage influences the rock mass in the SAG mill. Should the incoming ore be harder and the field of breakage insufficient to reduce the size, the ore stays in the mill longer since it is unable to pass through the grate. The net effect is an increase in rock mass, and the feed rate to the mill must be decreased appropriately to maintain rock to ball ratio. On the other hand, when the ore is soft, the field of breakage reduces the ore size rapidly and hence the rock mass decreases. To sustain a set rock mass, the feed rate must be increased. The complicating factor is that the incoming ore feed itself determines the breakage field.

1.1.2 **Flow through the grate and pulp lifters**: Discharge grates and pulp lifters play an important role in performance of the autogenous and semi-autogenous mills. The performance of the pulp lifters in conjunction with grate design determines the flow capacity of these mills. The function of the pulp lifters is simply to transport the slurry passing through the discharge grate into the discharge trunnion. Its performance depend on the size and design, the grate design and mill operating conditions such as mill speed and charge level. The difficulties associated with slurry transportation from SAG mills have become more apparent in recent years with the increasing trend to build larger diameter mills for grinding high tonnages. This is particularly noticeable when SAG mills are run in closed circuit with classifiers such as fine screens or hydrocyclones.

The performance analysis of conventional pulp lifter designs shows that a large amount of slurry flows back from the pulp lifter into the mill. The flow back depends on the size and design of the pulp lifters. Since the back face of the pulp lifter is the grate itself, the slurry readily flows back into the mill. Subsequently, the field of breakage diminishes when excessive slurry builds in the mill.

1.1.3 **Charge motion**: In a concentrator, all of the auxiliary equipment-pumps, conveyers, screens and hydrocyclones - and two primary resources-steel and electricity-serve primarily to maintain grinding action in the belly of the SAG mill. It is this action that dictates capacity. This being the case, it is understandable to observe this grinding action continuously from the control room and take whatever steps are necessary to keep the grinding field at its highest potential. Unfortunately, the grinding environment within the mill shell is very severe and none of the on-line instrumentation developed so far is able to survive the continuous impact of large steel balls. Since direct observation is impractical, the next available option is a simulation of the grinding field to gauge the intensity of grinding or lack of intensity of grinding.

1.1.4 **Mill power draft**: The field of breakage and flow through grates and pulp lifters influences each other and the net effect is the build-up of a hold-up level in the mill, which draws a certain power and this power draft is clearly linked with mill throughput. If the interaction can be understood then mill capacity can be understood much more clearly. Then the expectation of increasing capacity at the same level of power draft by one means or another can be safely evaluated.

The power draft of a SAG mill and its consequences are illustrated in Figure 1.2, wherein five days of operating data in a 32x14 ft SAG mill is plotted. The power draft of the mill is held between 6 and 7 MW, whereas tons per hour (TPH) of ore feed to the mill shows wide variations between 1000 tph to 1600 tph. When closely examining Figure 1.2, one finds that the feed rate drops whenever the power draft shows an increasing trend, whereas intuitive reasoning says that feed rate should be proportional to power draft.

The data shows that the specific energy consumption (kWh/tonne) of ore is not steady, as one would expect for a typical ore body. Even within a 24-hour time frame, where the feed ore hardness may be assumed constant, the variation in feed rate is drastic. The internal dynamics within the SAG mill, as exemplified by the three broad concepts, are causing wide fluctuations in grinding rate, which in turn is reflected as capacity.

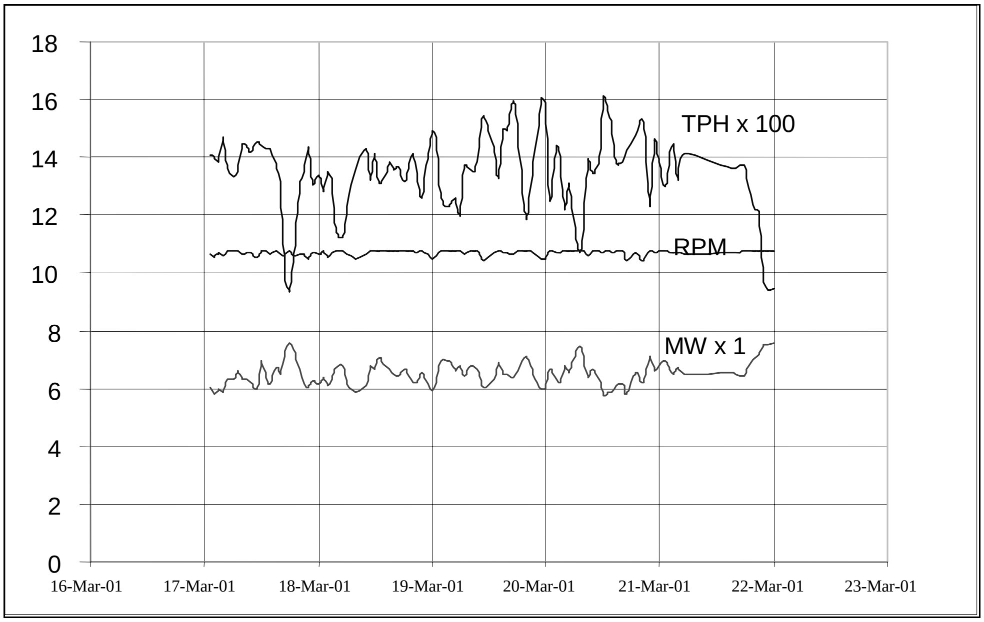

Figure1.2: Five days of plant operating data: 32x14 ft SAG circuit.
(TPH-fresh feed rate, MW-mill power in megawatts)

1.2 **SAG Mill Efficiency**

The energy efficiency of tumbling mills can be directly examined by looking at the motion of ore and grinding balls inside the mill. The make-up of the charge and the lifter bars attached to the inside of the mill shell can be designed particularly to maximize the mass of ore fractured per unit of energy spent. At the same time, the unnecessary collisions of steel balls against the mill shell can be reduced. Furthermore, the cascading charge flow can be altered in such a way as to maximize grinding efficiency. First, the shell lifters are designed in such a way the motion is fully cascading and that part of cateracting motion is made to strike in the vicinity of the toe. In such a charge motion regime both shearing action and impacts are fully utilized in grinding the ore.

The shell lifters are usually replaced once or twice a year. Pulp lifters survive two or three years. The design of these two important mill components has been largely based on trial and error and hence varies considerably between manufacturers. However over the years, important tools such as Millsoft™ and FlowMod™ have begun to help the designers to analyze and understand the influence of the internal components of SAG mills – shell lifters, grate and pulp lifters respectively. The following sections will discuss the basic principles and application of these two simulators.

Project Objectives

The overall objective of the project is to develop an integrated process model to enable the SAG mills to operate with high energy efficiency.

Phase 1:

To study the effect of individual variables such as charge filling, shell lifter configuration and design of discharge grate and pulp lifter on power draft of the mill by isolating the effect of one on each other.

Phase 2:

Conduct plant surveys at Kennecott Utah Copper Corporation and Cortez Gold Mines around the plant scale SAG mills to collect the operational data to simulate in pilot mill to optimize the performance of SAG mill and increase the energy efficiency.

2. EXECUTIVE SUMMARY

Many large mining operations around the world have one or more semi-autogenous (SAG) mills doing bulk of the work in their size reduction operation. The SAG mill is usually followed by a ball mill to finish the size reduction prior to the concentration step. In the past when primary, secondary and tertiary crushers fed material directly to large ball mills, the energy efficiency of the concentrator was determined for the most part by the ball mill operation, whereas now the energy efficiency of a plant often rests largely on the SAG mill operation. This has caused a shift of interest in optimization from ball mills to SAG mills.

Commercial SAG mill performance is determined by a large number of variables, both mine site variables and mill variables. In many cases these variables dictate production capacity seemingly randomly. Therefore a number of operating philosophies, each specific to a plant, have arisen. In almost all concentrators the SAG operation is an evolving operation. Every year, ways and means are sought to increase capacity, decrease energy consumption and prolong lifter and liner life. Newer designs of lifters and redesign of grates and pulp lifters are one of the routes.

The purpose of installing liners in grinding mills is to protect the mill shell from wear and efficiently transfer the energy to the grinding media. The liner profile in the grinding mill determines the energy transfer from the mill shell to the cascading and cataracting charge. However, over the useful lifespan of shell liner, wear leads to change in it's profile, which results in continuous change in the energy transfer to the cascading and cataracting charge. Also, cost of shell liners replacement and the production loss in relining represents a significant amount in the operating cost. Hence, a methodical study of liner wear and its influence on the breakage field is essential for understanding the influence of shell liner wear on mill throughput over the life span of line life.

In the last three decades, significant advances have been made in the modeling of tumbling mills. These investigations led to implementation of the well established techniques like population balance method and discrete element method for design and operation of tumbling mills. The present work details the development and implementation of a shell liner wear model based on Archard's wear law in the discrete element method simulation package *MILLSOFT*. This simulation routine can predict the wear profile of tumbling mill shell liners.

In addition, pilot scale experimental studies were carried out to analyze the effect of liner wear on the product size distribution and residence time distribution. It is shown that liners when slightly worn, after being in operation for about 4 weeks, operate at the highest energy efficiently.

The energy efficiency of these high-throughput grinding mills can be attributed to the field of breakage and slurry transport. The charge motion and breakage of particles inside the mill depends on the shell lifter design, while the discharge of ground particles is controlled by the grate and pulp lifters. The design of these mill components has been largely based on trial and error and hence varies considerably between manufacturers. A study done at the Cortez Gold Mines SAG mill shows how the redesign of the shell lifter brings about a reduction in energy consumption when slurry transport through the mill is adequate.

3 INDUSTRIAL DATA COLLECTION

Validation of the model is critical to know if the simulation is an accurate representation of the real systems considered. Every conceptual model needs to be validated, so that it can be regarded as accurately representing the real system. The validation is done by comparing the simulation results to what is generally accepted in the real system.

The shell liner wear model was incorporated in MILLSOFT^{TM} code. To validate the model, the project team tracked two sets of SAG mill liner and collect worn lifter profiles. The two SAG mills that were tracked are at Cortez Gold Mines, Crescent Valley, NV and Kennecott Utah Copper Corporation, Copperton, UT. After the SAG mill shutdown, the research team entered the SAG mill interior for measuring shell liner profiles. A flexible rubber tool was held against the lifter bars to get an impression of the lifter profile and the impression was transferred to the paper. The paper-profile was manually put on a grid scale to get x and y coordinates. These coordinates were then used in the calculations.

3.1 Cortez Gold Mines Survey

Three plant surveys were carried out to obtain the shell liner profile during the liner life cycle. The time line of the plant visits to Cortez Gold Mines (CGM) is listed in Table 3.1. The liners at Cortez Gold Mines were of high (seven inches height) and low type (five inches height).

Table 3.1 Time line of plant surveys conducted at Cortez Gold Mines

Survey	Date
Survey I	3rd March 2004
Survey II	8th April 2004
Survey III	2nd June 2004

The detailed operational and design characteristics of the SAG mill are given in. The profile of the new liner is shown in Figure 3.1. The corresponding liner profiles of the three surveys are shown in Figure 3.2, Figure 3.3

and Figure 3.4 respectively. The three liner profiles were compared to detect wear trend. Figure 3.5 illustrates the comparison of new and measured worn liner profiles.

The next step is to post-process the profiles to get the amount of steel consumption due to wear in SAG mill liners. The percent of steel consumption due to wear is essentially the same as percent change in the area under the liner profile. The areas under all the profiles were calculated using trapezoidal integration rule. Table 3.2 lists the area under high and low profiles. The percent changes in areas were also calculated and are listed in the same tables. The total steel mass consumption due to wear in kilograms, was also a point of interest to operators. Steel mass consumption due to wear of the liners were calculated and are listed in Table 3.3 and Table 3.4 respectively. The low liners were discarded after 14 percent of the steel mass was consumed due to wear and a new set of high liners were replaced. Before rejecting the existing high shell liners, total of 17.34 percent of steel mass was worn. The worn high liners became the low liners for the next cycle of operation.

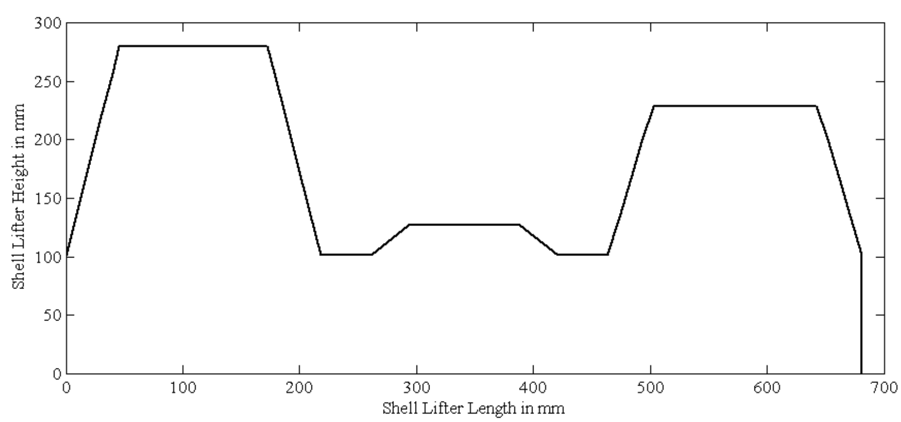

Figure 3:1 Profile of CGM SAG mill new shell liner installed on 14th January 2004

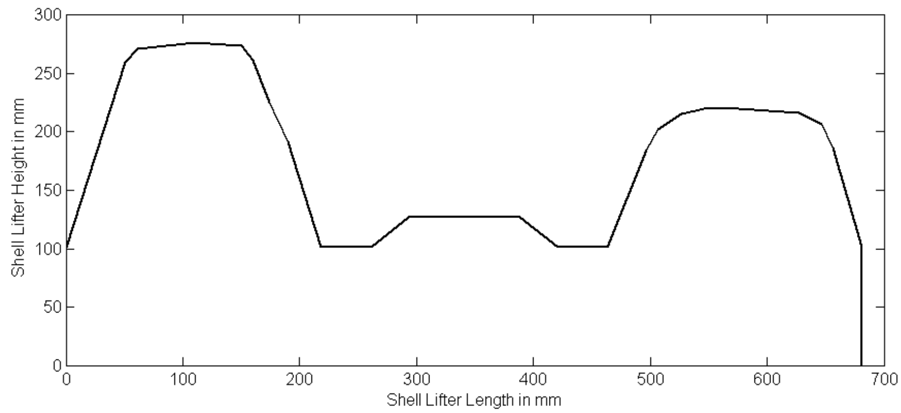

Figure.3:2 Average profile CGM SAG mill worn shell liner measured on 3rd March 2004

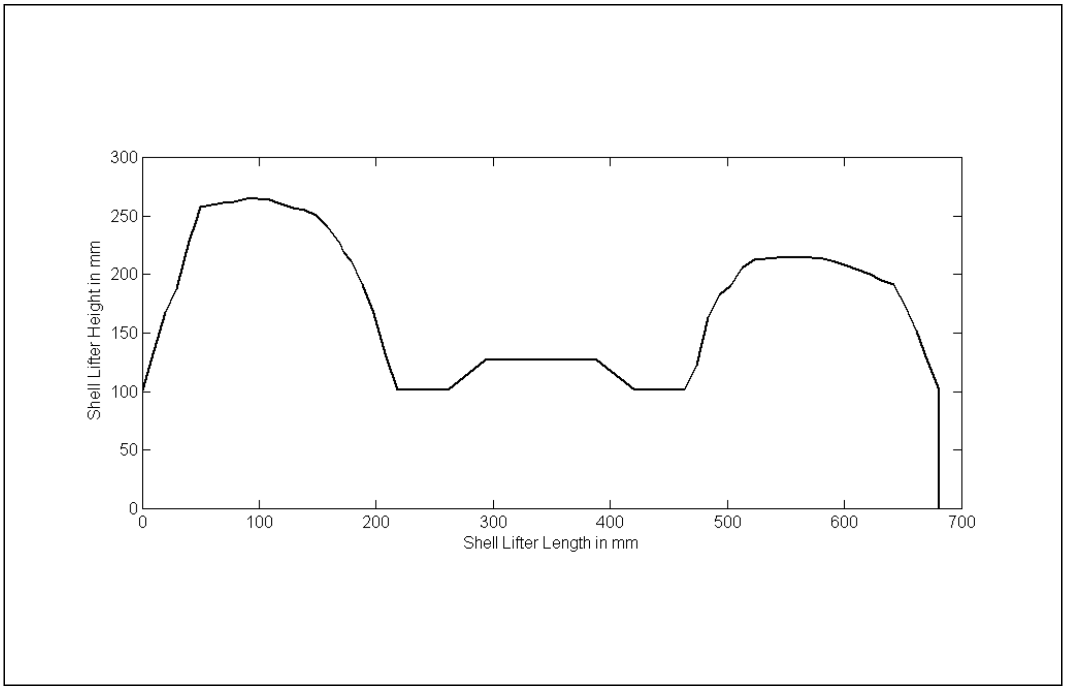

Figure.3:3 Average profile of CGM SAG mill worn shell liner measured on 8th April 2004

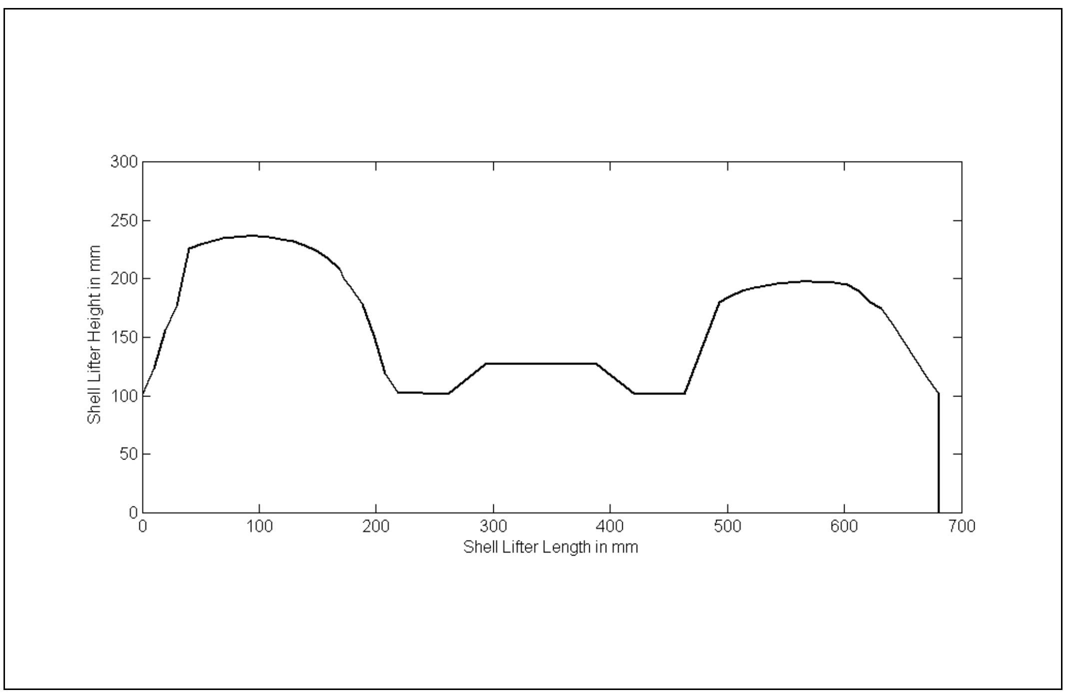

Figure.3:4 Average profile of CGM SAG mill worn shell liner measured on 2nd June 2004

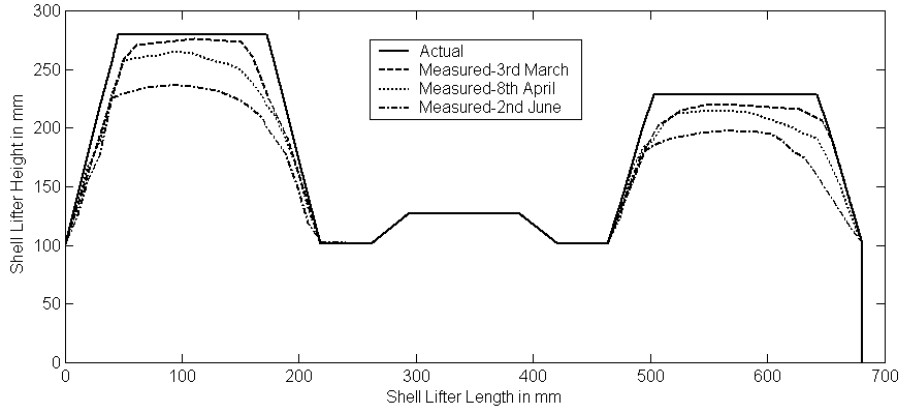

Figure.3:5 Comparison of CGM SAG mill shell liner measured profiles

Table.3:2 Calculated area under high and low liner profiles of CGM SAG mill at different time periods

Profile description (High liners)	Area under liner profile (mm^2)		% Change	
	High	**Low**	**High**	**Low**
Original	52903	44912	-	-
March 03rd 2004	49901	42147	5.67	6.16
April 08th 2004	48020	40835	9.23	9.08
June 2nd 2004	43727	38595	17.34	14.07

Table.3:3 Comparison of steel mass consumption for CGM SAG mill high shell liners at different time periods

Parameter	14th Jan	3rd March	8th April	2nd June
Number of lifters set	26	26	26	26
Cross sectional area of lifter (mm^2)	52903	49901	48020	43727
Length of each lifter set (m)	3.73	3.73	3.73	3.73
Density of steel (kg/m^3)	7800	7800	7800	7800
Mass of each lifter set (kgs)	1540.7	1453.3	1398.5	1273.4
Volume of each lifter set(m^3)	0.20	0.19	0.18	0.16
Total mass of shell lifter (kgs)	40058.9	37785.7	36361.4	33110.7
Total volume of shell lifter (m^3)	5.13	4.84	4.66	4.25
Mass consumption due to wear (kgs)		2273.16 (5.76%)	3697.47 (9.23%)	6948.20 (17.34%)

Table.3:4 Comparison of steel mass consumption for CGM SAG mill low shell liners at different time periods

Parameter	14th Jan	3rd March	8th April	2nd June
Number of lifters set	26.00	26.00	26.00	26.00
Cross sectional area of lifter (mm^2)	44912.00	42147.00	40835.00	38595.00
Length of each lifter set (m)	3.73	3.73	3.73	3.73
Density of steel (kg/m^3)	7800.00	7800.00	7800.00	7800.00
Mass of each lifter set (kgs)	1308.00	1227.47	1189.26	1124.03
Volume of each lifter set(m^3)	0.17	0.16	0.15	0.14
Total mass of shell lifter (kgs)	34008.02	31914.33	30920.86	29224.70
Total volume of shell lifter (m^3)	4.36	4.09	3.96	3.75
Mass consumption due to wear (kgs)		2093.7 (6.16%)	3087.16 (9.08%)	4783.32 (14.06%)

3.2.2 Kennecott Utah Copper Corporation Survey

Similar surveys were carried at the Kennecott Utah Copper Survey (KUCC) SAG mill. The shell liners at KUCC SAG were installed on 9th March 2004. Two plant surveys carried out on 12th May 2004 and 14th July 2004. The mill liners were discarded after 14th July 2004.

The new liner profile is shown in Figure 3.6. The two average worn liner profiles are shown in Figure 3.7 and Figure 3.8. The wear of the liners is even on both sides because the mill operates in both directions. In a similar manner, calculations of area and steel mass consumption due to wear were carried out and are listed in Table 3.5 and Table 3.6 respectively. The shell mill liners were discarded after 58.44% of steel mass consumed due to wear.

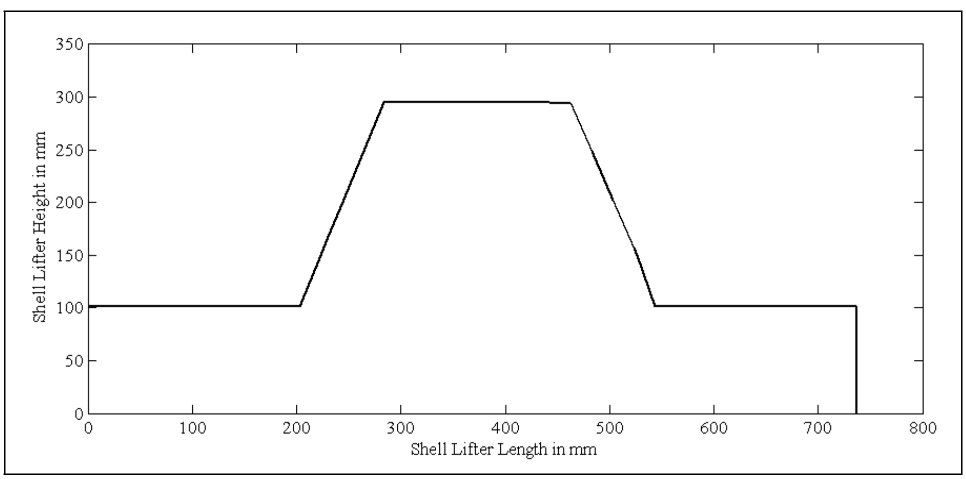

Figure.3:5 Kennecott Utah Copper Corporation SAG mill new shell liner profile installed on 9th March 2004

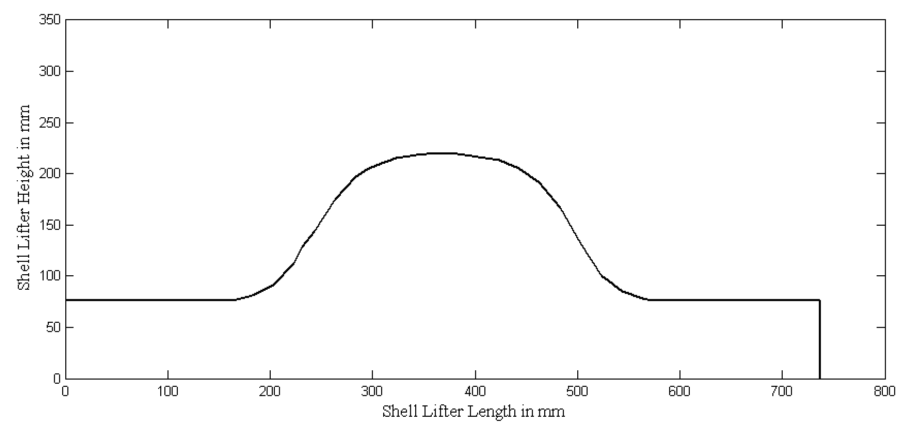

Figure.3:6 KUCC SAG mill average worn shell liner profile as of on 12th May 2004

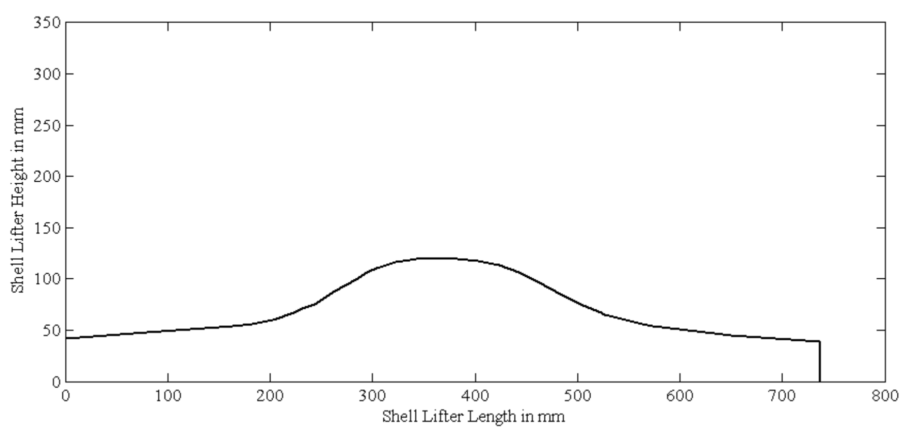

Figure.3:7 KUCC SAG mill average worn shell liner profile as of on 14th July 2004

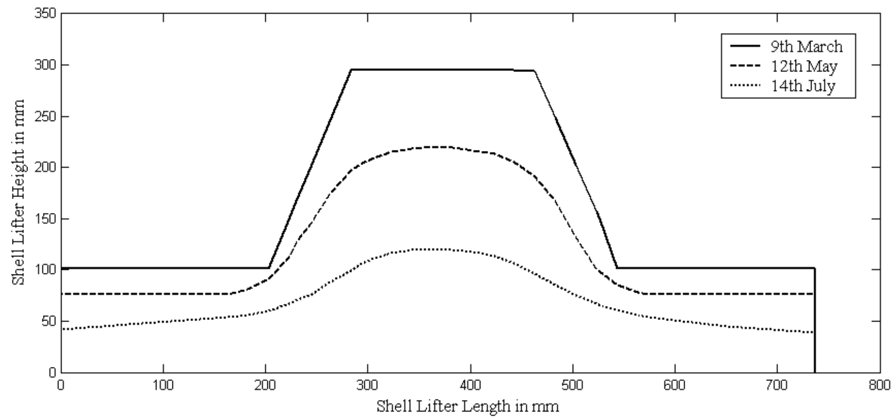

Figure.3:8 Comparison of KUCC SAG mill shell liner measured profiles at different time periods

Table.3:5 Calculated areas under shell liner profiles of KUCC SAG mill at different time periods

Profile description (High liners)	**Area under liner profile (mm^2)**	**% Change**
Original	125400	-
May 12^{th} 2004	91122	27.33
July 14^{th} 2004	52100	58.44

Table.3:6 Comparison of steel mass consumption for KUCC SAG mill shell liners at different time periods

Parameter	**New lifters**	**May 12^{th}**	**July 14^{th}**
Number of Lifters set	88.0	88.0	88.00
Cross Sectional Area of Lifter (mm^2)	125400	91122	52100
Length of Each Lifter set (m)	2159	2159	2159
Density of Steel (kg/m^3)	7800	7800	7800
Mass of Each Lifter set (kgs)	2064.1	1534.5	877.3
Volume of Each Lifter set(m^3)	0.26	0.20	0.11
Total mass of Shell Lifter (kgs)	181647.7	135036.8	77208.5
Total Volume of Shell Lifter (m^3)	23.2	17.3	9.9
Mass consumption due to wear (kgs)		46,610.89 (27.33%)	104,439.2 (58.44%)

4 RESULTS AND DISCUSSION

4.1 Wear Model Predictions

Estimation of wear rate for shell liners in any grinding process is near to impossible by conducting laboratory scale experiments. Long hours of operation are required for getting significant wear in mill shell liners. But, wear in shell liners is significant in plant scale SAG mills. For industrial operations, the shell liners are changed on an average in every 8 months. Industrial surveys were carried out at two plant scale SAG mills. The liner profiles and steel loss due to wear of liners were obtained from the surveys. The surveys were also carried out on both SAG mills for validating the simulation outputs.

4.1.1 Cortez Gold Mines (CGM) SAG mill simulations

Mineral processing plant at CGM is located in Crescent valley, NV for processing mined gold ore with a tonnage of 450 tons per hour. The plant can treat up to 10,000 tons of gold ore per day. Single SAG mill in close circuit with recycled pebble crusher is installed in the processing plant. The characteristics of the SAG mill are given in Table 4.1. Fifty-two rows of high and low lifters are present in the SAG mill. The design dimensions of high and low lifters are shown in Figure 4.1. Simulations were carried out to observe the wear profile trends for both high and low lifters. Because of simulation time constraint, only twelve-revolution simulations were carried out to obtain the wear map across the liner.

The average wear data obtained over the twelve revolutions was used for evolution of liner profile over the next thirty to fifty days of operation. Next, in MILLSOFT simulation the lifter profile corresponding to the simulation result was constructed and again wear calculations were carried out for another 30 days of operation. Simulations were carried out until the end of life cycle, where the worn high lifter reaches the height of new low lifter, after which the low lifter is discarded and replaced with a new high lifter, and the existing worn high lifter becomes the low lifter. Table 4.2 outlines the timeline of the simulations and average wear rate of liners obtained from simulations.

Table 4.1 Dimensions and operating variables of the CGM SAG mill

Mill diameter	26 ft
Mill length (effective grinding length)	10.5 ft
Mill speed in (% critical)/RPM	78/11.6
Percentage of filling	27
Top ball size dimension	5 inch
Number of shell lifters (high and low)	52

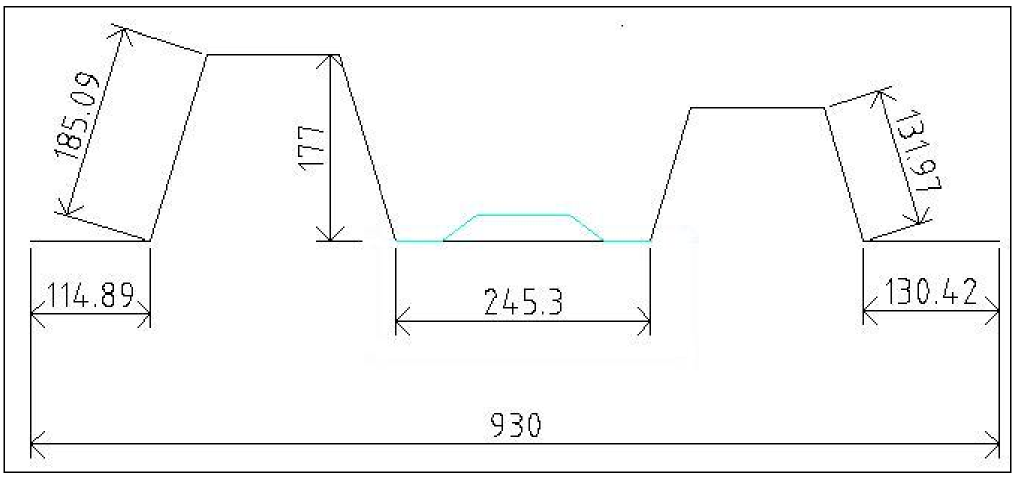

Figure 4.1 Dimensions of the high and low shell lifters of CGM SAG mill

Table 4.2 CGM Simulation results

Lifter Life	**Mass consumption due to wear**		**Number of Days of Operation**	**Average wear rate liners (mm/h)**	
	High	**Low**		**High**	**Low**
Period – I	5.76	6.16	38	2.68E-7	2.32E-7
Period – II	9.23	9.08	34	1.66E-7	1.26E-7
Period – III/ EOLC	17.34	14.06	55	1.57E-7	1.22E-7

It can be observed from Table 4.2 that wear rate of high lifter is more then wear rate of low lifter in all the three periods. Since, the high lifters have more exposed area then low lifters for abrasion and impact collisions; the wear rate is correspondingly higher. Also, as the number of days of operation increases, the liner wear rate decreases. For the first 38-days period, the wear rate is very high compared to the next 34-days periods because the sharp corners of the new liners wear faster then flat or curved surfaces. For high and low liners the changes in liner wear rate from period II to period III are minimal because of absence of sharp corners in these phases. The change in charge profile due to change in liner shape for the three different periods is shown in Figure 4.3.

The charge motion also plays an important role in liner wear. The higher wear rate of the liner in the initial phase can be accounted to the higher liner charge angle (shoulder angle) compared to other periods. High lift angle leads to more cataracting and impact collisions near the toe area of the charge. Figure 4.2 shows wear pattern across cross section of a liner for period–I. The wear pattern across the liner clearly shows that the corners wear out faster than the rest of the liner surface. The leading edge and top wall of the liner are subjected to more wear then any other section of liner. The real profiles at all the time periods collected from the plant surveys were illustrated in this section. Figure 4.4 shows the new liner profile along with the simulated worn out liner profile for all the periods. Simulation was carried out at 78% critical speed and 27% mill filling for all three periods. The volume of material removed near the leading edge and on the top wall of the liner is comparatively higher than from other parts of the liner. The face angle of the liner is increasing for all the simulations. The liner was discarded after 15% weight of material was lost due to wear.

The mine site SAG mill wear profiles were collected as described in preceding section, for carrying out comparison studies. A good agreement of the lifter profiles has been found between the measured and the discrete element predictions at different steps. The comparison of simulated and original profiles are shown in Figure 4.5.

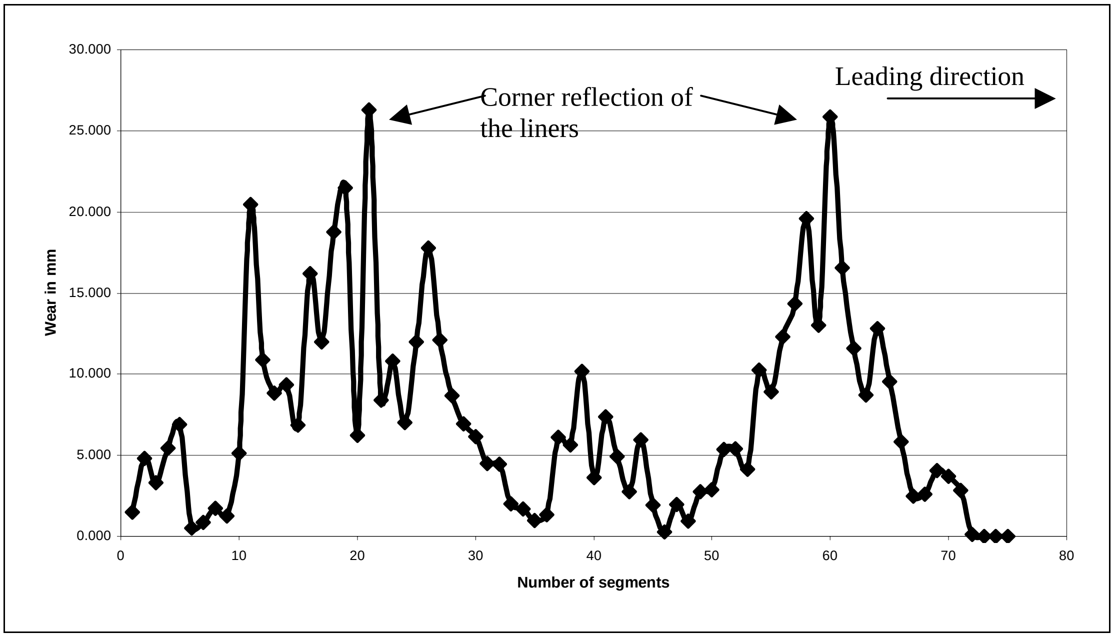

Figure 4.2 Typical wear patterns across the cross section of a liner for CGM Simulation

Steel consumption due to wear of shell liners are shown in Table 4.6. It can be observed that the percentage change in predicted steel loose and actual steel loose is not beyond 4.5 % for all the periods.

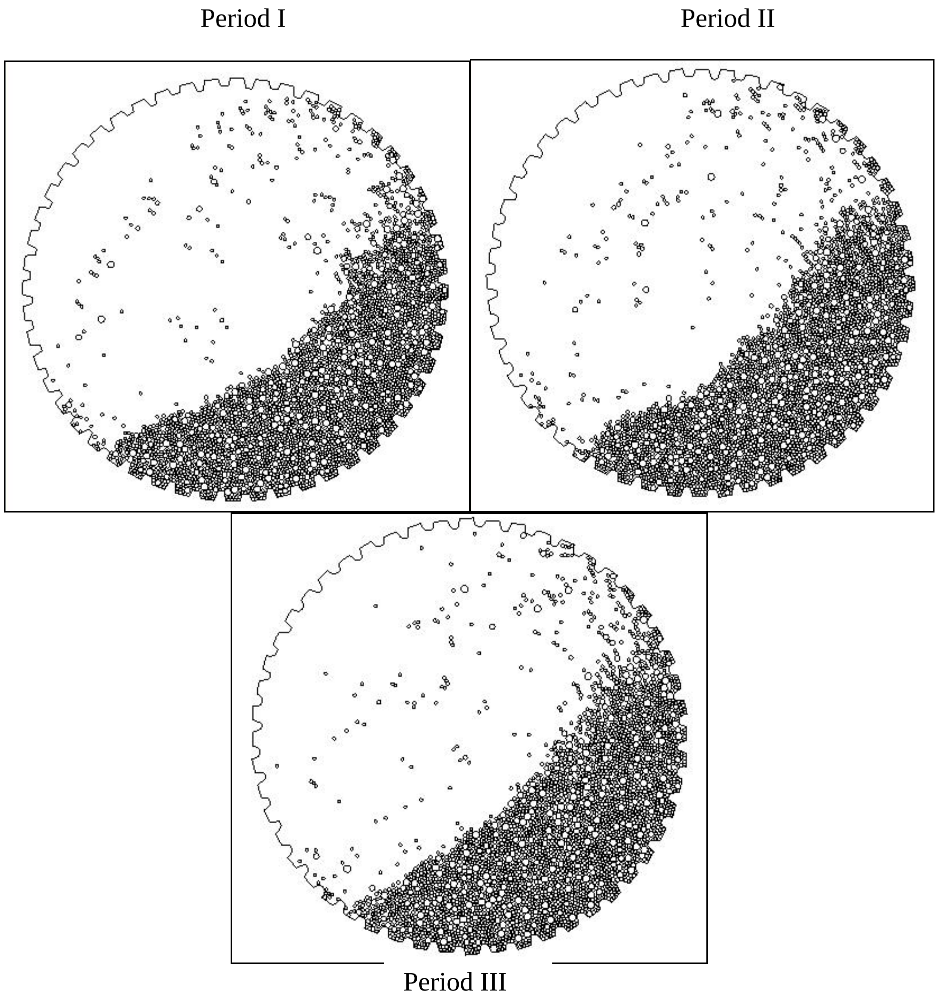

Figure 4.3 Charge profiles in all the three periods of CGM simulations

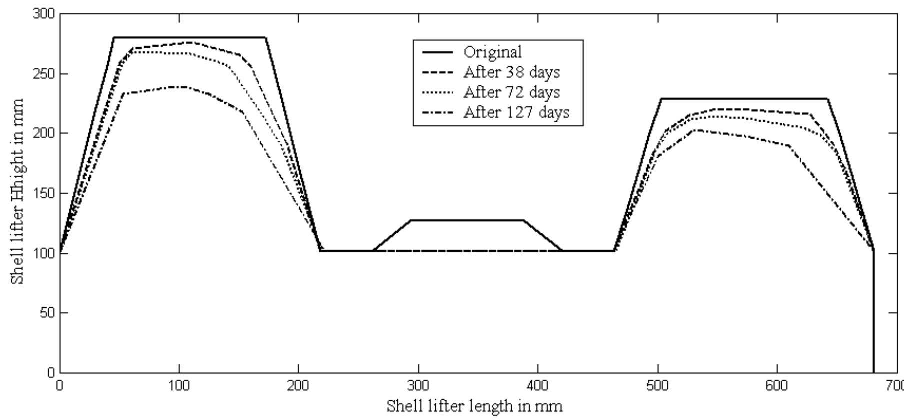

Figure 4.4 Simulated shell liner profiles at different time period for CGM operations

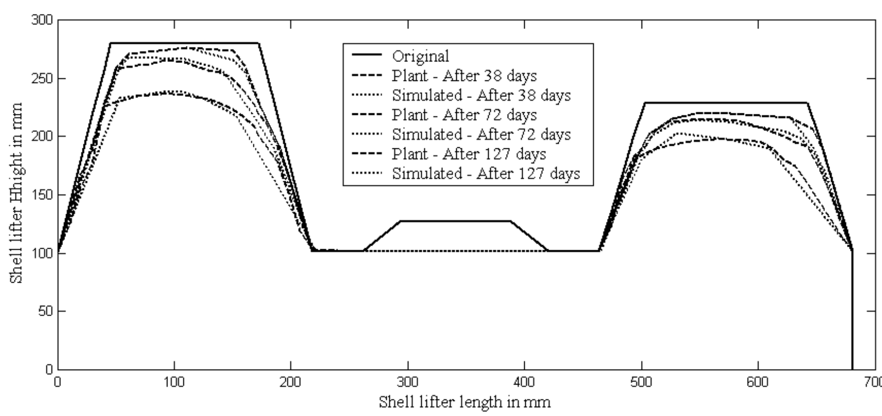

Figure 4.5 Validation of the simulated profiles with the industrial profiles for CGM

Table 4.6 Total steel consumption due to wear of high and low shell lifters over three different periods

Periods	Actual steel consumption (Kgs)		Simulated steel consumption (Kgs)		% Change in prediction	
	High	Low	High	Low	High	Low
Original	-	-	-	-	0	0
Period – I	2273	2094	2362	2190	+ 3.91	+ 4.58
Period – II	3697	3088	3758	3183	+ 1.64	+ 2.98
Period – III	6948	4784	7191	4919	+ 3.49	+ 2.82

4.1.2 Kennecott Utah Copper Corporation (KUCC) SAG mill simulation

The design and operating variables of the SAG mill are shown in the Table 4.7. The mill had eighty eight rows of shell liners. The mill was operated in both directions. The new shell liners profile is shown in Figure 4.6.

Plant scale survey was done on March 9^{th} and May 12^{th} for collecting the worn liner profile. Wear simulations were carried out for first 63 days of operation with the brand new profile as the starting profile.

The worn profile was built based on the wear data obtained from the simulation with new shell liners. With the worn shell liner obtained from the above simulation, new simulation was carried out for next 62 days to get the final end of life cycle profile. At these time these liners were discarded and new set of liners were installed in the mill. Because of the simulation time constraint, only twelve-revolution simulations were carried out to obtain the wear map across the liner. The average wear rates for the first and second phase simulation are given in Table.

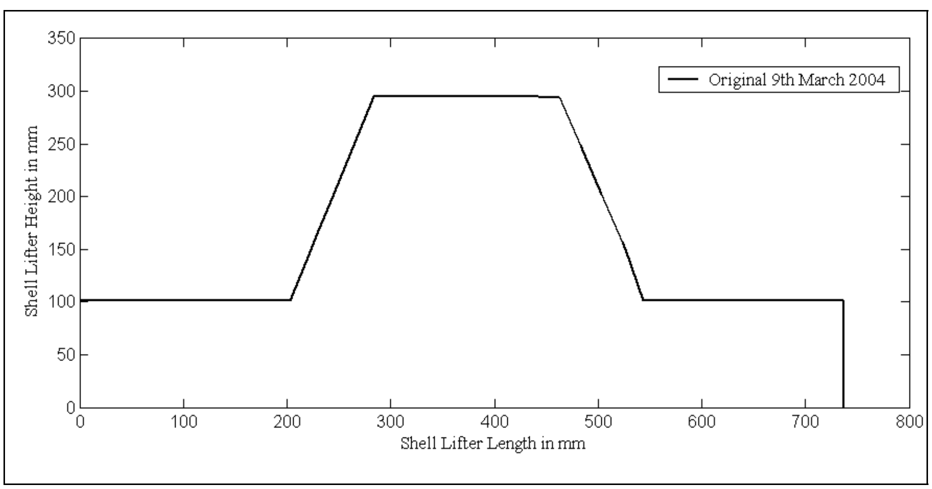

Figure 4:6 KUCC SAG mill new liner profile installed on 9^{th} May 2004

Table 4.7: KUCC Simulation results

Lifter Life	Number of Days of Operation	Average wear rate liners (mm/s)	Percent Mass consumption due to wear
Period – I (March 9th – May 12th)	63 days	7.8E-06	27.5
Period – II/EOLC (May 12th - July 14th)	62 days	18.1E-06	58.4

As the liner wears out, more of its surface gets exposed to both impact and abrasion wear. Hence, the wear rate of the liner is very high at the final stage of its life. In contrast to the CGM simulation results, where the wear rate of the shell liner increased with time, the KUCC simulation results show a opposite trend. Since, CGM liners were discarded very early just after consumption of approximately 15% mass of liner by weight but in the KUCC case, the shell liners were retained till approximately 60% liner mass was consumed. A typical wear pattern across the liner surface for KUCC SAG mill shell liner is shown in Figure 4.7. The wear profile across the liner shows clearly that the corners wear out faster compared to other section the liner. For example in Figure 4.8 the corners wear depth is 120mm for the period one simulation where as the shell plate wears depth is just 20mm. The liner wear near the top edge is higher compared to liner wear values in the other section of the liner. Because the mill is a bi-directional mill, symmetry in the shell liner wear pattern was observed. The charge profile in both of the simulation is shown in Figure 4.9. In second period simulation, because of the worn liners, the charge cataracting zone shrunk compared to the first period simulation.

The simulation results are shown in Table 4.8. A comparison of the simulated profiles with the average plant profiles is shown in Figure 4.10. It is apparent that the model predicts the liner profile accurately. In the second phase simulation results, the predicted shell plate profile is lower compared to the actual profile from plant survey. Hence, the predicted shell plate wear rate is higher compared to the actual wear rate. The steel consumption predictions are in the range $\pm$ 2.5% of the actual steel consumption value obtained from the plant. Table 4.8 gives the predicted and actual steel consumption due to shell liner wear for the two time periods of the liner life.

From the experience with KUCC and CGM it can be concluded that Archard's modified wear law shown in Equation 3.3, seems adequate for liner description in tumbling mills.

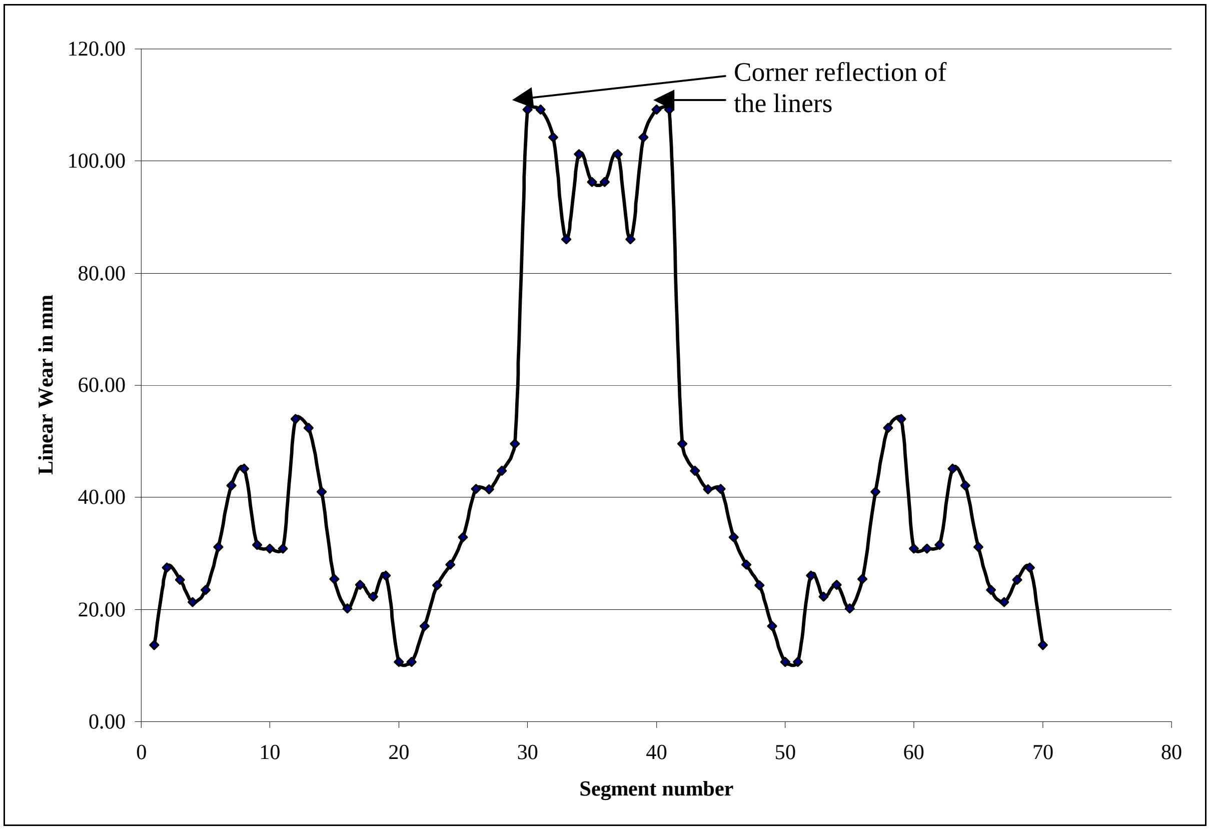

Figure.4:7 Typical wear patterns across the cross section of a liner for KUCC simulation

Table.4.8 Actual and simulated steel consumption due to wear of KUCC SAG shell liners over two time period

Periods	Actual steel consumption (Kgs)	Simulated steel consumption (Kgs)	% Change in prediction
Original	-	-	0
Period – I	46,610	45,922	- 1.47
Period – II	104,439	106,991	+ 2.45

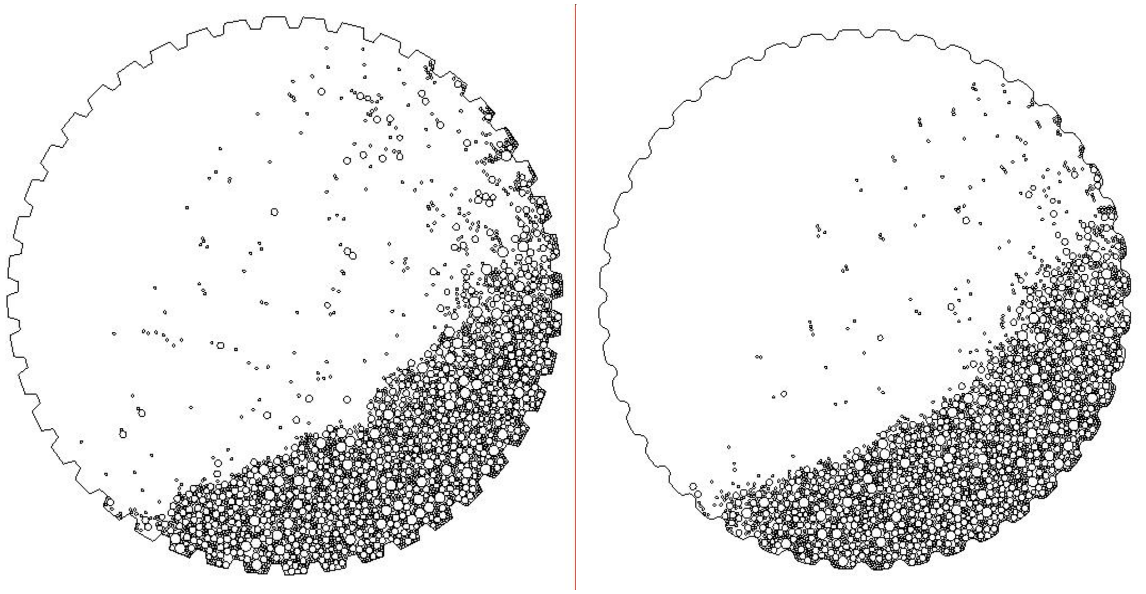

Figure.4: 8 Charge profiles for the two KUCC simulations (Period 1 and Period 2)

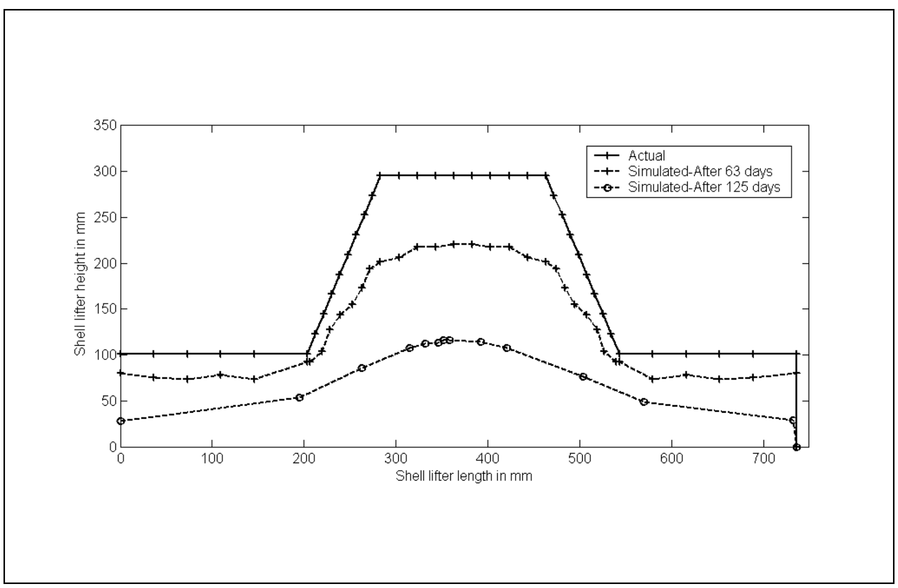

Figure.4:9 Simulated profiles of KUCC simulations

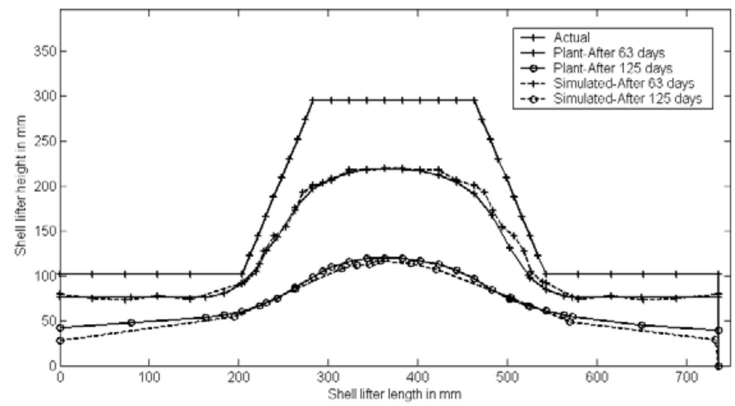

Figure.4:10 Comparison of simulated profiles and collected profiles

4.2 Sag Mill Study At Cortez Gold Mines

The aforementioned analysis of shell and pulp lifters is illustrated with the work done at Cortez Gold Mines, Crescent Valley, Nevada [16]. The grinding circuit consists of a 26X13 ft. SAG mill in closed circuit with a pebble crusher. The discharge of the SAG mill is screened on a 0.75-inch screen and the oversize material is fed to the cone crusher. The undersize is sent to the ball milling circuit. The typical SAG mill feed is 400 stph, which varies anywhere between 250-550 stph, depending on the ore-type. At least five different ore types are encountered at this mine site.

Over many years the SAG shell lifter has evolved to a high-low pattern with a typical high lifter dimension of 7-inch height, 5-inch wide at the top and 17^0 face angle on both sides. The low lifter dimensions are: 5-inch height, 5-inch top width and 17^0 face angle on both sides. The mill shell has been drilled for 52 rows of shell lifters. The open area of grate is 7% with the typical 2.75-inch square opening.

The plant operating work index shown in Fig.4.31 shows an average of 15 kWh/st in the year 2004 till the liner change and then decreasing since then to about 13 kWh/st. This reflects the efficient usage of energy in SAG mill as well as the ball mill operation, which is probably getting a relatively finer feed.

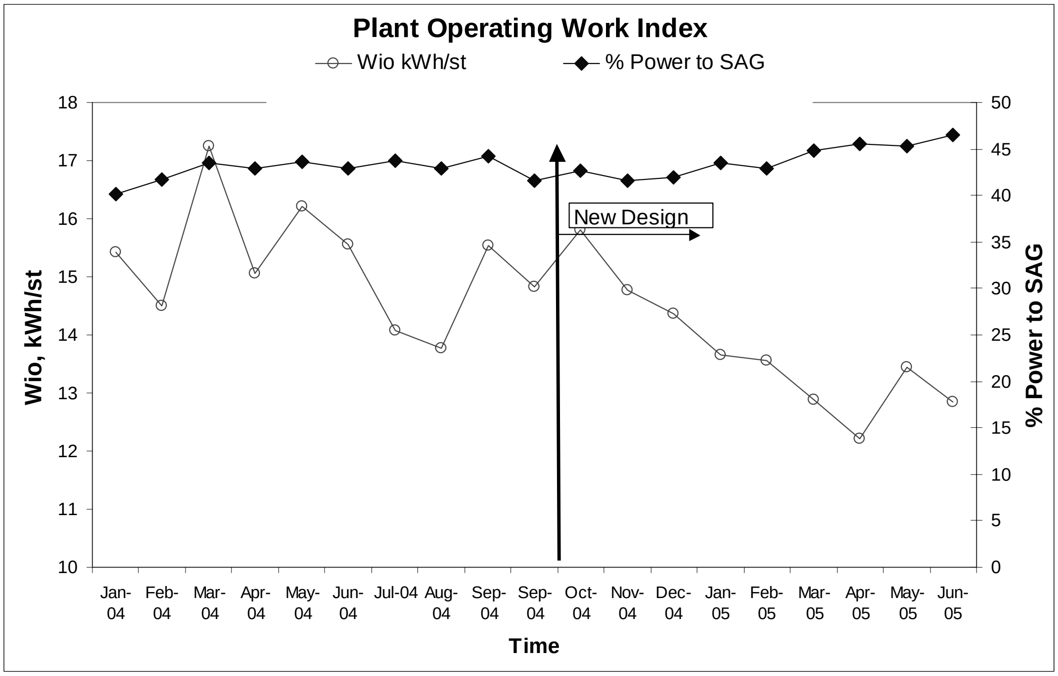

Figure 4.31: Monthly record of plant operating work index.

4.2.1 Grate and pulp lifters: First, a review of the grate plate and pulp lifter showed that 7% open area was adequate for handling the daily-targeted tonnage. In fact, the grate openings were found to be free of balls or rocks during many inspections. The discharge capacity of the grate is 482 m^3/hr of slurry. However, FLOWMOD calculations indicated that the pulp lifter diminished this flow to 382 m^3/hr as a result of flow back phenomena. However, this flow rate is adequate to handle current daily tonnage. Also, the radial distribution of grate opening in the mill periphery indicated that some advantages could be gained by redistributing the open area in the most optimal flow regime. The recommendation was implemented in a subsequent grate redesign. In summary, the grate and pulp lifter combination was operating more than satisfactorily although there is always room for further increase in the pulp discharge capability of the mill.

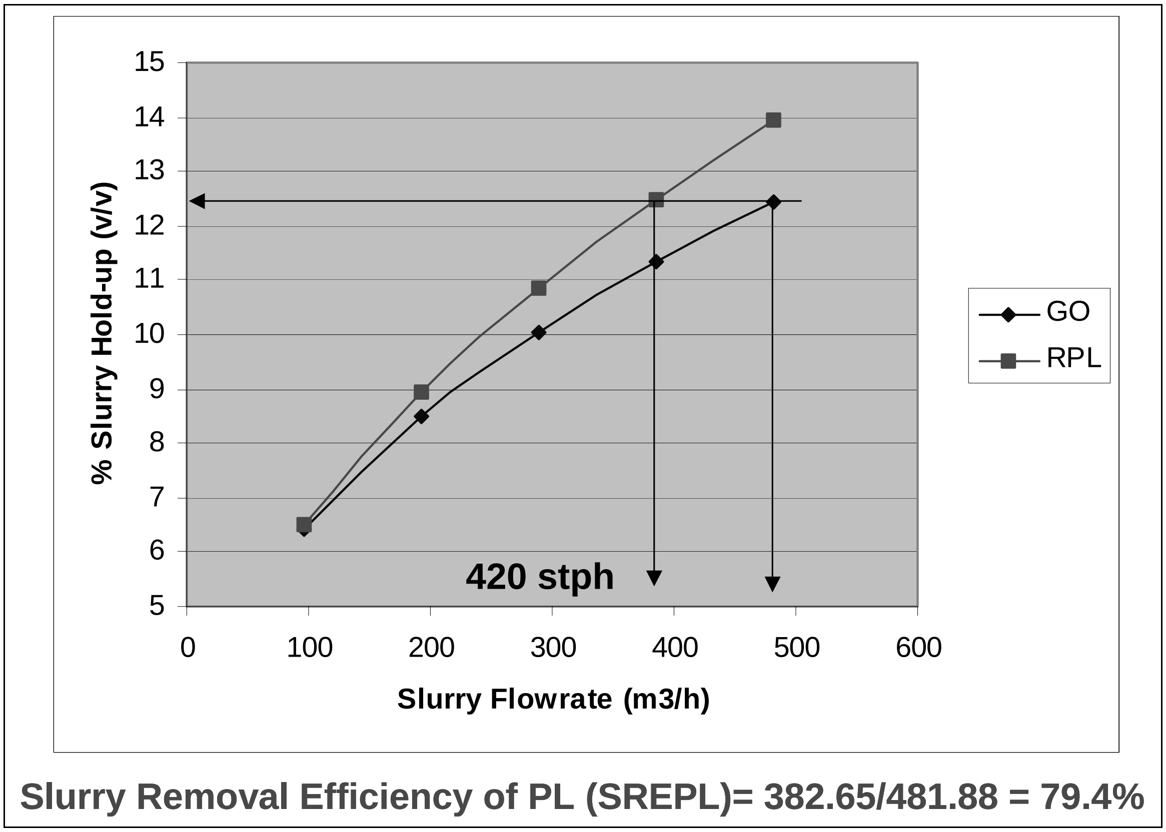

Figure 4.32: FlowMOD calculation pf slurry flow rate through the SAG mill.

Figure 4.32 shows discharge flow rate as a function of fractional slurry hold-up. At the current operating conditions, increasing the open area to 9% and redistributing the slots radially may increase the discharge flow rate to 450 m^3/hr.

It is very critical that the pulp transport capacity of the mill must be set at its maximum value before changing shell lifters. The shell lifters may increase the production of fines, but there must be the capacity to discharge these fines.

4.2.2 High-low shell lifter experience: The high-low shell lifter design leaves a gap of 10 inches between the lifters. As a result, caking between lifters was very severe as shown inFigure 6. Due to cake build-up the effective height of the high-lifter over the base is a mere 2-inch. Figure 4.33 shows the MILLSOFT simulation of charge motion with the high lifters. The 17^0 lead face angle causes cataracting between 8 o' clock and 9 o' clock positions of the mill circle.

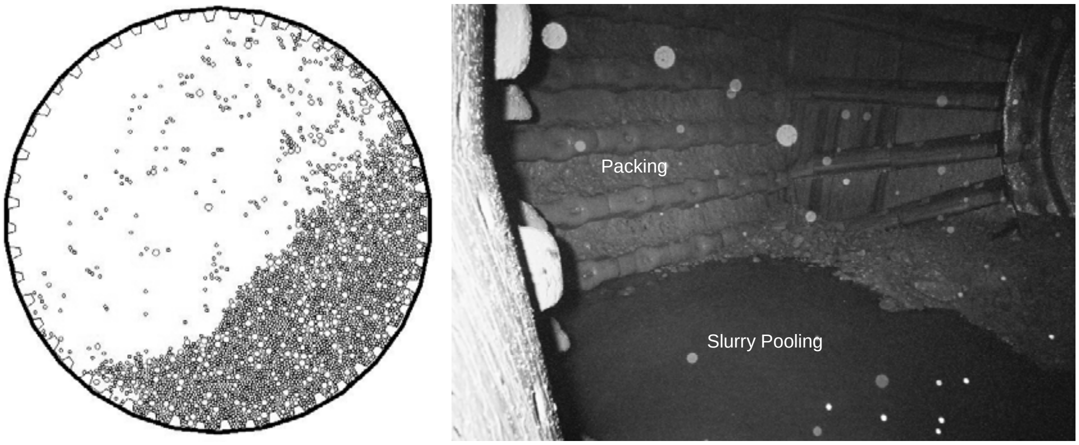

Figure 4.33: Charge motion with high-low lifters

With the use of 5-inch grinding balls and exposed shell plates the cataracting caused consistent and moderate level damage to the mill shell. Some of the lifters were broken and in other places there was severe peening. As a result the mine experienced unscheduled SAG mill related down time every month. Figure 4.34 shows the unscheduled down time for a two-year period.

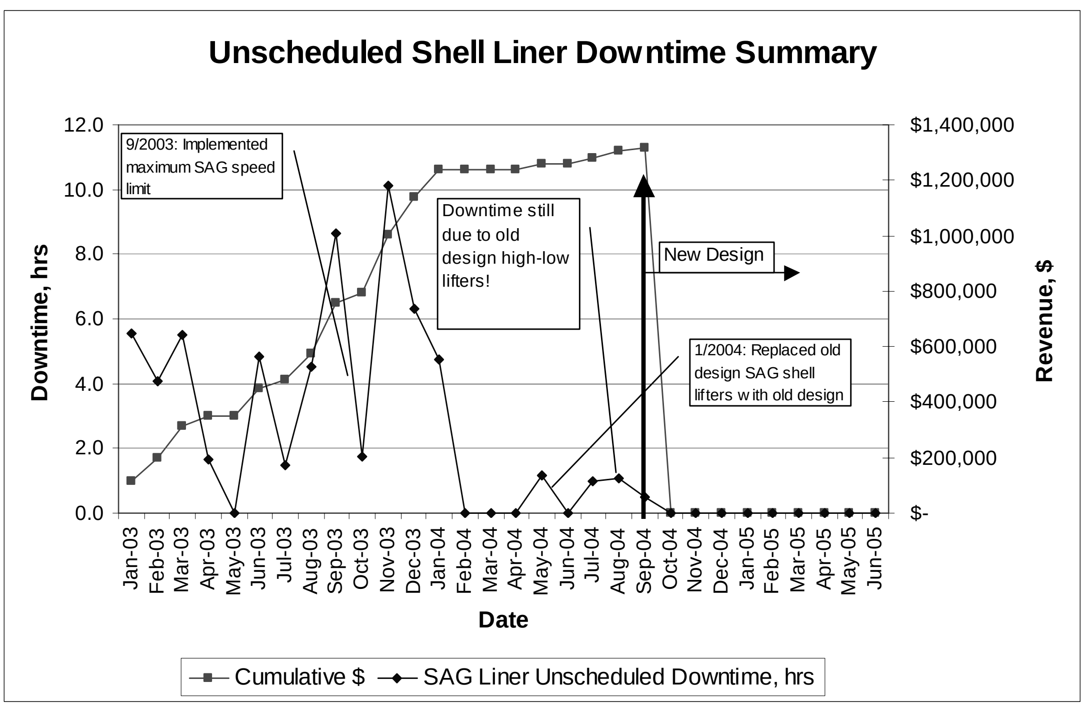

Figure 4.34: Unscheduled downtime.

It is seen that even as the lifter is in the last four months of operation leading up to September 2004, there is down time due to lifter damage. Crash stop done during this period shows cake build up between lifters and a fair amount of slurry retention within the mill (see Figure 6).

4.2.3 Shell lifter redesign: A decision was made to reduce down time and increase energy efficiency with a new design of lifters. In particular, it was decided to bring the 5-inch ball trajectory to the toe of the charge by correct choice of leading face angle. Furthermore, it was decided to eliminate every other lifter row to minimize packing and maximize lift as well as increase mill volume. Figure 4.35 shows Millsoft simulation of the new design (9 inch height, 5 inch top width with 28° leading and trailing face angle). As anticipated the cataracting charge lands near the toe of the charge at around 7 o' clock position of the mill circle. The simulated power draw was consistent with operating power draw. This type of liners with leading face inclined at a steep angle (22°-35°) has been well documented in the literature. A number of mine sites, including Alumbrera [11], Collahuasi [10], Candelaria, Los Pelambres and others [1] have had success with these lifters. Besides the design criteria for optimal trajectories for 5 inch grinding balls a number of other issues such as safety of liner handling, safety of mill noise, inching drive capability, load on the mill motor and mill start-up had to be addressed and taken care off.

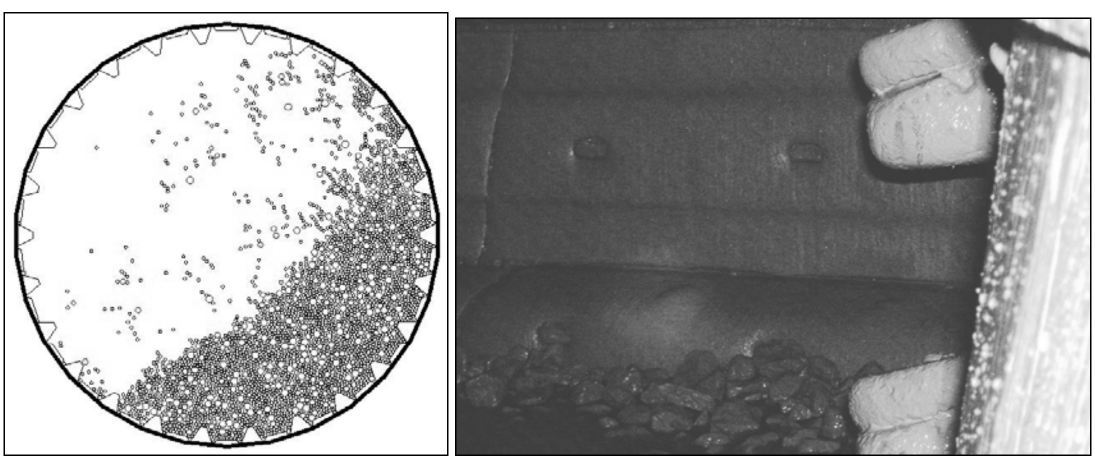

Figure 4.35: Charge motion with new lifters

4.2.4 Slurry transport and load build-up in the mill: Slurry transport out of the mill plays an important role in determining SAG capacity. Figure 4.36 shows the cyclical behavior of the SAG circuit three weeks after change over to the new lifter design. In particular, the feed to the SAG mill cycles up and down in every two hours. Mill bearing pressure exhibits similar behavior. The cyclical behavior is primarily due to pulp lifter returning part of the slurry passing through the grate back into the mill. In other words back flow in the pulp lifter returns part of the slurry to the mill. As a result the mill slurry hold-up increases and the controller cuts the feed to the SAG mill. This cyclical behavior points that the circuit capacity can be improved by a proper choice of pulp lifters.

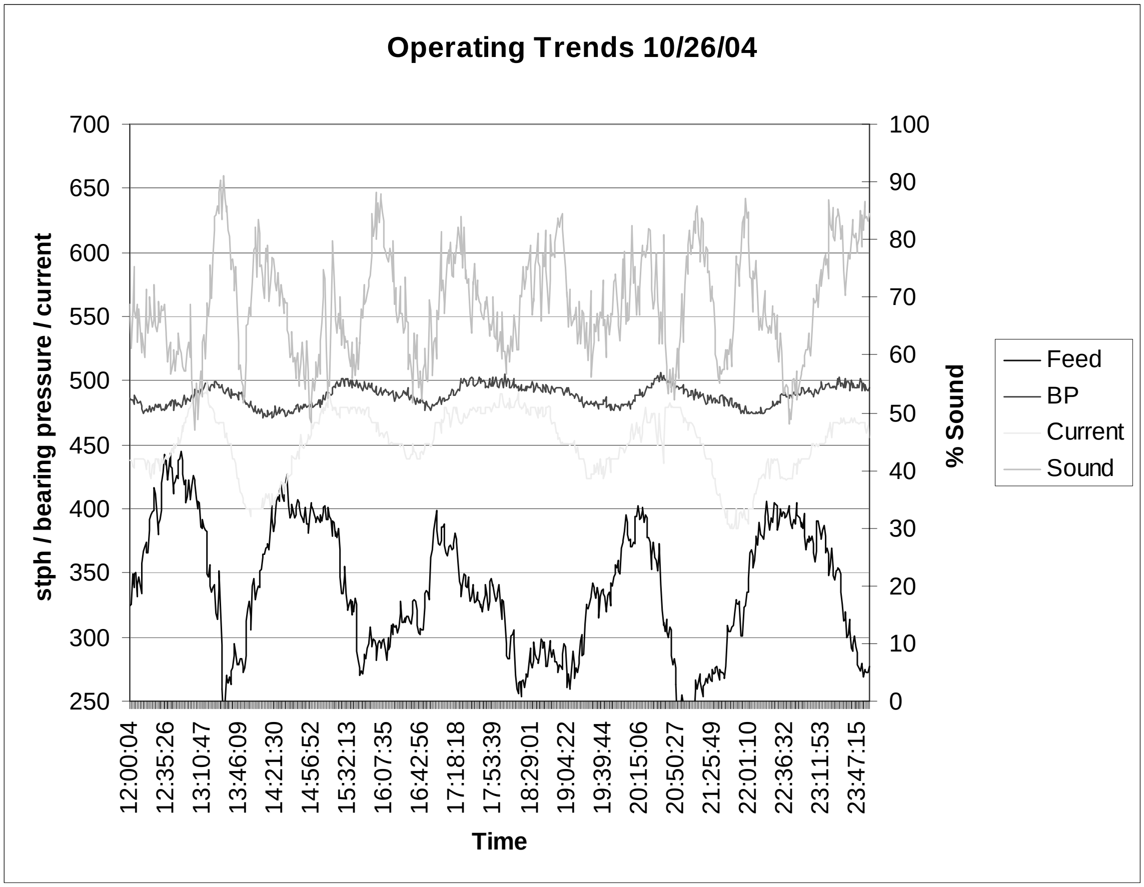

Figure 4.36: Cyclical behavior of the mill

4.2.5 Impact on power draw and energy consumption: The main focus here is the energy efficiency of the SAG mill. Figure 10 shows the SAG throughput before and after installation of new shell lifter. The SAG circuit maintains more or less the same throughput after lifter installation. It should be kept in mind that ore type is changing from day to day and it will take over 4 months to encounter all different ore types. The major advantage gained with the new lifter design is shown in Figure 4.37. The mill bearing pressure staying at steady value both before and after the lifter change implies that the mill load is unaffected by the design of the new lifters. However, the mill feed rate steadily increased after the lifter change. These two observations imply that the new lifter design is bringing about an efficient breakage of ore particles. Thus the mill throughput increases while maintaining the same load.

The critical impact of the new lifter design is illustrated in Figure 4.38. The SAG mill exhibits a very definite reduction in power draft. It is estimated that the power decreases is in the 230-370 kW range. Hence energy consumption per ton of ore milled decreases by 0.3-1.3 kWh/ton. This energy saving is in the 10% range. Furthermore 1-10% reduction in recirculation to the cone crusher was noticed due to efficient impact breakage of critical size material. All of these amounts to a significant operating cost reduction.

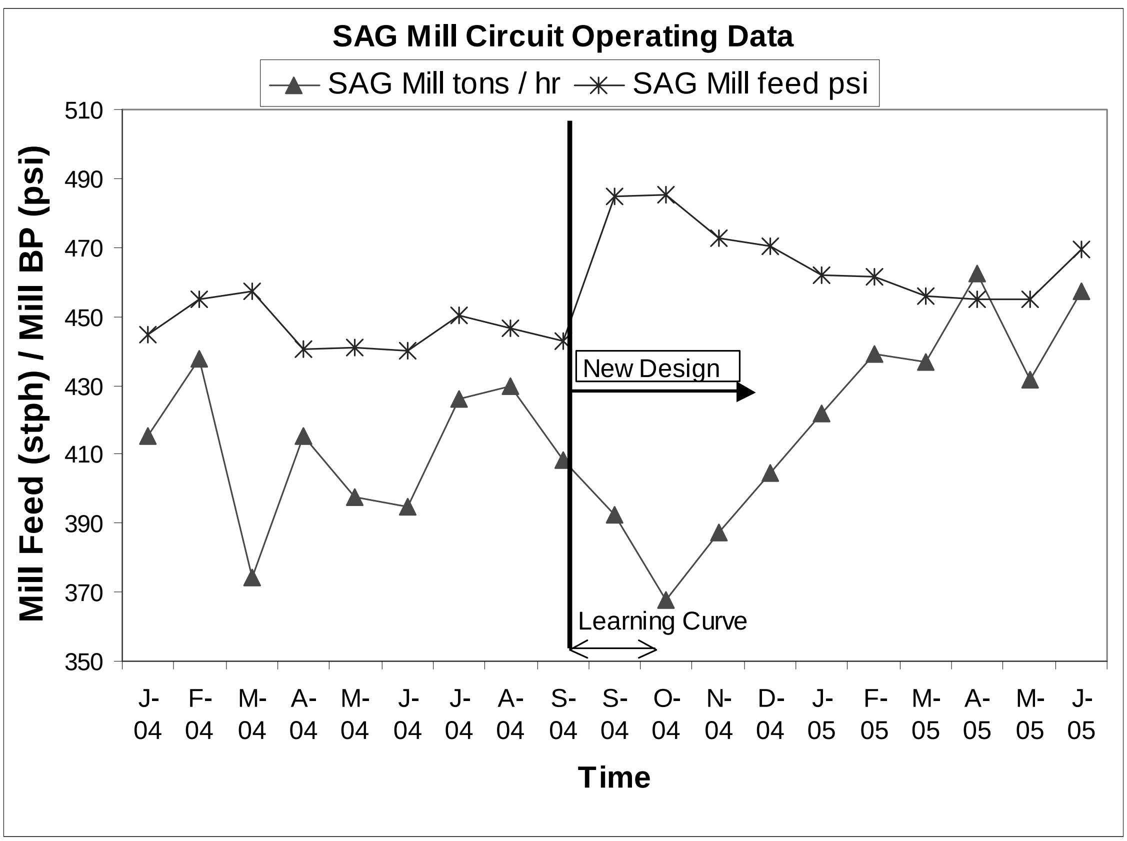

Figure 4.37: SAG mill operation before and after installation of new shell lifters.

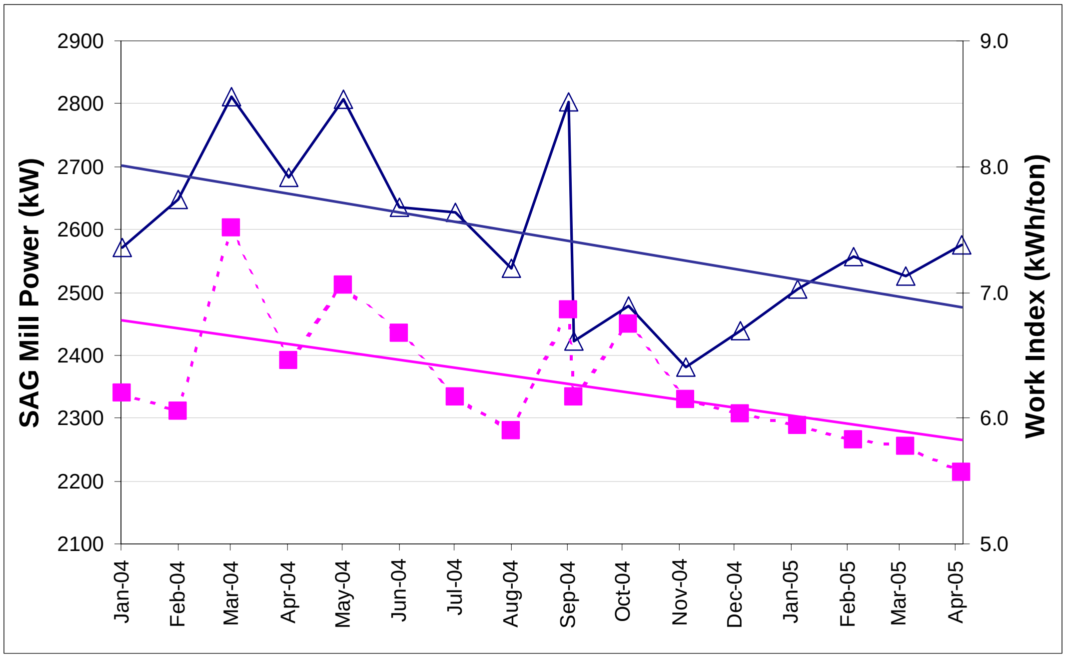

Figure 4.38: SAG mill power data

A more efficient ball trajectory or charge motion means that there is less of direct impact of grinding ball on shell plates and lifters. As a result grinding ball consumption and steel losses in lifter wear must be impacted. At Cortez Gold Mines operation grinding ball consumption could not be tracked via digital control system. However, it was noticed that in 16 weeks of operation only 2.5 inches of lifter height was lost due to wear. It was estimated that the new design costs 57kg/day of steel loss compared to 84kg/day for the previously installed lifter, a 47% savings in steel loss. Furthermore, in the 9 months of operation leading up to June, 2005 the mill did not experience any down time due to cracked shell plates, severely peened lifters, broken lifters or leaky bolts. Thus we find that proper design of shell lifters leads to a decrease in energy consumption per ton of ore.

5. CONCLUSIONS

The discrete element method coupled with Archad's wear law can predict shell liner wear rates in tumbling mills. Plant scale surveys at Cortez Gold Mine and Kennecott Utah Copper Corporation were conducted for validating the developed wear model. A good agreement was found between the measured liner profiles and simulated liner profiles.

It is shown that the design of both shell lifters and grate-pulp lifter assembly are crucial for optimal performance of the SAG mills. The design of shell lifters, which control the charge motion thus the breakage field, can be optimized using Millsoft™ - a discrete element numerical method. FlowMod™ is a steady state simulator to optimize the design of grate and pulp lifters to handle the given flow through the mill. It estimates the slurry hold-up inside the mill and shows its dynamic surface at any mill operating condition. These two tools were employed in the study of the SAG mill at Cortez Gold Mines. First the flow or discharge capacity of grate and pulp lifter were analyzed. It was found that the capacity is adequate for meeting daily tonnage. Next, the redesign of shell lifters readily resulted in 230-370 kW reduction in mill power draw while maintaining the same throughput level. The SAG mill circuit exhibits cyclic loading behavior indicating that there is room for further increase in capacity via pulp lifter redesign.